Simplified analytical methods and experimental correlations of damping in piping during dynamic high-level inelastic response

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ABSTRACT

Simplified methods for predicting equivalent viscous damping are used to assess damping contributions due to piping inelastic plastic hinge action and support snubbers. These increments are compared to experimental findings from shake and snap-back tests of several pipe systems. Good correlations were found confirming the usefulness of the simplified methods.

1 INTRODUCTION

Nuclear power plant piping designs of the last decade have incorporated many seismic restraints and snubbers to assure adequacy to withstand earthquakes. The design methods have conservatively utilized very low damping values. In the past few years much experimental damping data of piping responding elastically has been gathered. This led to new proposals by industrial groups, such as the Pressure Vessel Research Council (PVRC), for higher design damping allowables. The ASME adopted an interim Code Case N-411.

Interest in high-level inelastic response and tests-to-failure have resulted in USA research programs sponsored by the U.S. Department of Energy (DOE), reported by Lindquist et al. (1986); the U.S. Electric Power Research Institute (EPRI), reported by English (1985), and Jaquay, Larson and Tang (1986); and the U.S. Nuclear Regulatory Commission (NRC), reported by Chen, DeVita, and Onesto (1986), Severud et al. (1986), Guzy (1986), Anderson et al. (1987), and Weiner (1987).

In West Germany, KWU and Interatom have sponsored work on high level inelastic pipe response tests and analysis methods; refer to Haas et al. (1985), Peters and Busch (1986), and Weiner, Peters, and Busch (1987).

The effective equivalent damping associated with the inelastic response is also of interest for use in simplified analyses. Numerous equivalent viscous damping determination methods have been studied by Hadjian (1982), and others. Hadjian pointed out the differences that are found depending upon the assumptions regarding the structure equivalent stiffness of elasto-plastic systems. Bohm, Tagart and Wallach (1985), emphasized the need for considering inelastic damping data. Accordingly, more correlations of test data to prediction model data are desired to clarify this technology.

2 SIMPLIFIED ANALYTICAL METHODS

Under NRC sponsorship, simplified methods for calculating modal equivalent viscous damping for plastic hinges and snubbers were used to assess damping energy distribution in four pipe systems at high-level response.

The methods described herein provide simple techniques for calculating the total modal equivalent viscous damping coefficient. It is determined as the sum of damping due to (a) plastic hinges, (b) snubbers, and the pipe system exclusive of (a) and (b).

The equivalent viscous damping coefficient, ξ , for the piping system is approximated by:

$$(1) \qquad \xi = \Delta W/[4\pi(KE)] = \Delta W/[2\pi \sum_{i}^{n} (m_i \, x_i^2)]\omega_N^2$$

where, ΔW = energy loss per cycle and KE = maximum kinetic energy or strain energy of the system, m_i = i^{th} mass, x_i = max. amplitude of i^{th} mass, and ω_N = circular frequency of mode N. The energy loss, ΔW, is made up of those losses due to plastic hinges, snubbers, and the other damping sources.

The plastic hinge energy loss, ΔW_p, is approximated by

$$(2) \qquad \Delta W_p = 4 \sum_{i=1}^{K} \left[M_{pi} \left(\theta_{mi} - \theta_{yi} \right) \right]$$

where, K = number of plastic hinges in system, M_{pi} = effective limit moment of plastic hinge i, θ_{mi} = maximum angle amplitude hinge i rotates through, and θ_{yi} = angle amplitude to initiate plastic hinge i yielding.

The snubber energy loss, ΔW_s, is approximated by:

$$(3) \qquad \Delta W_s = \pi \sum_{j=i}^{L} \left[C_j \; \omega_N \; X_{Mj}^2 \right]$$

where, C_j = damping coefficient of snubber j, ω_N = circular frequency of mode N, and X_{Mj} = maximum displacement of snubber j.

3 PLASTIC HINGE DAMPING CORRELATIONS

The four piping systems of Figure 1 were shake-tested to high-level inelastic response. Table 1 provides correlations of calculated damping increments due to plastic hinges to total system damping levels estimated from the test response. It is noted that in applying eq. (1) and (2), quasistatic elastic-plastic system deformation solutions for increased modal acceleration loads are employed to evaluate the system displacements and angles and equivalent system stiffness and maximum kinetic or strain energy (Weiner, 1987).

Regarding the HEDL 1" system (Table 1), the high-level test (2.5 g's ZPA) of this small bore heavily insulated pipe system with one mechanical snubber, experimentally revealed dynamic magnifications equivalent to 40 to 50 percent damping. At low levels, the piping system was elastic and the equivalent damping was about 10 percent. The calculated equivalent increment of damping for one plastic hinge was 16 percent and with two hinges it was 29 percent. The single mechanical snubber provided only 1 percent damping. Thus, adding 30% to the 10% low-level damping gives a good correlation to the experimental 40% measured equivalent damping value.

4 SNUBBER DAMPING INCREMENTS

The 16" diameter insulated stainless steel pipe system of Figure 2 was tested. Table II shows a typical damping calculation. Figure 3 shows the effects of load level and the total system damping and the calculated snubber damping.

Small bore piping 1" to 3" diameter, with heavy insulation were tested and total system damping levels in the 5 to 12 percent range were found. Snubber damping increments calculated for these piping were in the 1 to 2 percent range.

5 CONCLUSIONS

A number of correlations of the calculated damping values per the above methods have been made with piping experimental findings. These comparisons of calculated and experimental data, of typical piping systems at multiple levels of response, are presented in this paper. Good correlations were found. The simple methods provide a useful tool in assessing the extent plasticity and snubbers add to piping system damping during high-level inelastic response.

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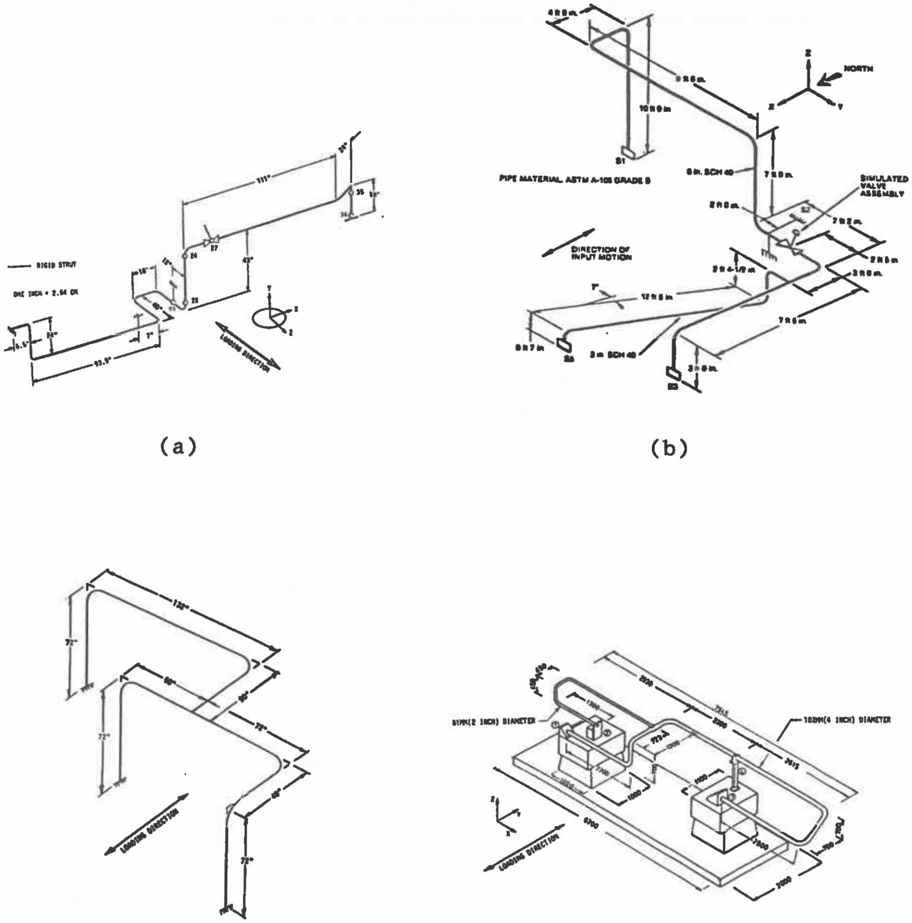
ACKNOWLEDGMENTS

The findings reported herein are based on work sponsored by the U.S. Nuclear Regulatory Commission Division of Engineering Safety. The authors especially appreciate the guidance of Mr. D. J. Guzy and Mr. J. E. Richardson of the NRC.

TABLE 1 PIPE DAMPING DURING SHAKE TEST HIGH-LEVEL INELASTIC RESPONSE

SYSTEM	PIPE DIAM(S).	MATERIAL	EXCITATION TYPE	MAX BASE INPUT, G'S	MAX.STRAIN RANGE, % ESTIMATE	ESTIMATED SYSTEM TEST DAMPING, %	CALCULATED PLASTIC HINGE EQUIVALENT VISCOUS DAMPING, %
HEDL 1" $f_1 = 2\ H_z$ Ref. [1]	1 in (25.4 mm)	304 S.S.	Sinusoidal 12-18 Cycles at 2 H_z	2.5	2.5 Ref. [1]	40-50 Ref. [5]	29
ETEC 6" $f_1 = 5\ H_z$ Ref. [4]	6 in./3 in.	SA 106B	Seismic Sinusoidal 10 Cycles at 4 H_z	30 ZPA 18	4 4-8 Ref. [8]	13-22 19 Ref. [8]	18 (Mode 1) 20 (Mode 2) 16
ETEC 3" $f_1 = 5\ H_z$	3 in.	SA 106B	Seismic Seismic	14 ZPA 30 ZPA	8 14	* *	30 (Mode 1) 16 (Mode 2) 36 (Mode 1) 22 (Mode 2)
KWU 4/2" Ref. [9]	4 in./2in.	Aust. S.S.	Harmonic at 8.9 H_z	4	1.8	*	5 (Mode 3)

*NO DATA AVAILABLE OR PUBLISHED YET.



(a)

(b)

(c)

(d)

Figure 1. Pipe systems shake-tested to inelastic levels: (a) heavily insulated small bore (1" diam.) stainless steel; (b) uninsulated mild steel (6" diam.); (c) uninsulated mild steel 3" diam.); (d) uninsulated stainless steel (4" and 2" diam.).

TABLE 2 16" DIA. PIPING SNUBBER DAMPING ESTIMATE FOR SNAP BACK TEST

NODE NO	SNUBBER TYPE	INITIAL MAX LOAD, LBS*	DAMPING COEF. C, LBS-SEC/IN	SNUBBER INITIAL MAX DISPL., X, IN.	SNUBBER ENERGY LOSS/CYCLE $E_S = \pi C \omega X^2$, IN-LB
H-2	PSA-3	20	20	.000	0
H-3	-3L	85	85	.002	2
H-4	-3L	90	90	.002	2
H-5	TWO-1L	2@795	2(2000)=4000	.014	56
H-6	TWO-3	2@60	2(60) =120	.001	1
H-9	TWO-3	2@650	2(700) =1400	.013	24
H-11	TWO-1L	2@215	2(1000)=2000	.007	10

$$2\pi \omega_N^2 \sum (m_i x_i^2) = 2\pi(2\pi \cdot 5)^2 (.389) = 2400.$$

$$\sum \pi C_i \omega_N X_N^2 = 95$$

$$\xi_{SN} = \frac{95}{2400} = 0.04, \text{ Say } 4\%.$$

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*BASED ON STATIC ANALYSIS AND MAGNIFICATION FACTOR = 2.0 FOR SUDDEN SNAP BACK

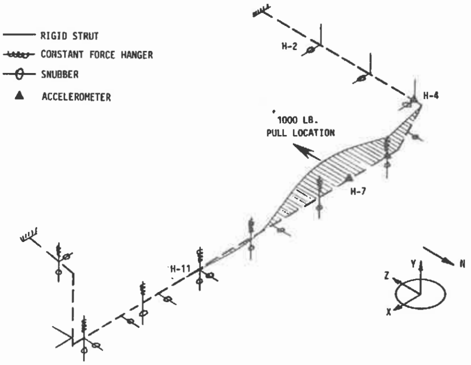

Figure 2. Piping mode shapes, pull at H-7 for 16" diameter insulated stainless steel piping system, first mode, f = 5.0 HZ

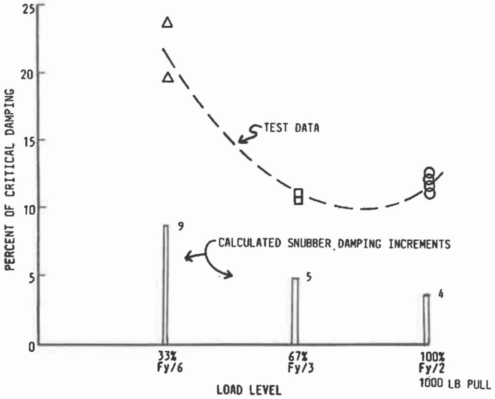

Figure 3. Effect of load level on damping, pull at H7, accelerometer H7Z